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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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SOME OBSERVATIONS OF OCEAN THERMAL

RESPONSE TO TYPHOON PASSAGE

by

Benjamin Lewis Holt, Jr.

December 1976

Thesis Advisor: R. L. Elsberry

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The fact that typhoons cause a cooling of the upper oceanic layers during their passage is well documented. This case study establishes the magnitude of this cooling for 17 western Pacific super-typhoons during the period 1968 to 1972. Digitized bathythermograph (BT) records for the typhoons were screened to acquire points before and after typhoon passage that met selection criteria. The selected BT records were then assigned a weight that reflected the number of hours before or after the

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typhoon passed its closest point of approach (CPA). The resulting data file for the 17 typhoons was analyzed using several techniques. It was found that there is a positive correlation between the magnitude of mixed-layer cooling and the distance from the typhoon path, as well as with wind velocity at the BT site. Mean mixed-layer cooling near the storm path ranged from .70° to 2.0°C with a maximum cooling of 4.8°C. At the outer reaches of the storm's influence (300 nmi) the mean mixed-layer cooling range was -.09°C to .36°C. The results of the analysis compare favorably with single storm analyses in the Atlantic and a 14 storm analysis in the Pacific. Mixed-layer depth information was subjected to the same analysis as the mixed-layer cooling but the results were inconclusive.

Some Observations of Ocean Thermal

Response to Typhoon Passage

by

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Lieutenant, United States Navy
B.S., United States Naval Academy, 1970

Submitted in partial fulfillment of the
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ABSTRACT

The fact that typhoons cause a cooling of the upper oceanic layers during their passage is well documented. This case study establishes the magnitude of this cooling for 17 western Pacific super-typhoons during the period 1968 to 1972. Digitized bathythermograph (BT) records for the typhoons were screened to acquire points before and after typhoon passage that met selection critieria. The selected BT records were then assigned a weight that reflected the number of hours before or after the typhoon passed its closest point of approach (CPA). The resulting data file for the 17 typhoons was analyzed using several techniques. It was found that there is a positive correlation between the magnitude of mixed-layer cooling and the distance from the typhoon path, as well as with wind velocity at the BT site. Mean mixed-layer cooling near the storm path ranged from .70° to 2.0°C with a maximum cooling of 4.8°C. At the outer reaches of the storm's influence (300 nmi) the mean mixed-layer cooling range was -.09°C to .36°C. The results of the analysis compare favorably with single storm analyses in the Atlantic and a 14 storm analysis in the Pacific. Mixed-layer depth information was subjected to the same analysis as the mixed-layer cooling but the results were inconclusive.

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I. INTRODUCTION

A. BACKGROUND

Several authors have reported dramatic cooling of the ocean's mixed layer temperature (MLT) in the wake of typhoons/hurricanes. Studies have been carried out in areas of the Atlantic [Black 1971, Hazelworth 1968, Landis and Leipper 1968], the Gulf of Mexico [Jensen 1970, Leipper 1967, McFadden 1967], and the Pacific [Fedorov 1972]. The instruments utilized in measuring the MLT have included airborne infrared radiometers, aircraft expendable bathythermographs (AXBT's), bucket thermometers, merchant ship injection temperatures, bathythermographs (BT's), and temperature sensors on the NOMAD buoy in the Gulf of Mexico. In many of the previous studies information from more than one of the instruments was used to provide a data base from as few as one and as many as 14 storms. The analyzed storms included a few that had maximum wind speeds in excess of 130 knots which placed them in the "super-typhoon" category. The decreases in the MLT after typhoon/hurricane passage ranged from 0.9°C to 3.0°C, with a single study maximum of 5.0°C (Leipper 1967]. Other studies [Black 1972, Elsberry et al 1976] have shown the magnitude of the MLT decrease to be dependent upon storm intensity and the speed of the storm's advance. Yet another study [Jensen 1970] related the dependence of the MLT decrease to the temperature of the mixed layer prior to storm passage.

There are at least four known processes that can affect a decrease in the MLT during and after typhoon/hurricane passage [Hazelworth 1968].

Most studies [Black 1972, Elsberry et al 1976, Fedorov 1972, Leipper 1967] agree that mechanical mixing and upwelling along the storm path coupled with horizontal advection are the dominant processes that affect the mixed layer. The occurrence of these processes has been confirmed by modelling [Elsberry et al 1976] and by observation [Black 1972, Fedorov 1972, Leipper 1967].

The one problem that has hampered authors of previous studies is the availability of "real time" open-ocean, mixed layer temperature and depth structure records in sufficient quantity to render the analyses results statistically sound.

B. OBJECTIVE

The objective of this study is to determine the magnitude of the MLT cooling after typhoon/hurricane passage by using the digitized BT files of the U.S. Navy's Fleet Numerical Weather Central at Monterey, California as a single data source. Furthermore, this study will demonstrate that a sufficient quantity of pertinent data, within a 25-day data envelope centered on the storm passage, exists and the subsequent results were statistically relevant. This study will expand the sampling area, usually within the RMW, to 300 nmi from either side of the storm track. To provide evidence of upwelling and/or mechanical mixing the mixed layer depth (MLD) data will be subjected to the same analysis techniques as the MLT data. A secondary objective of this study is to prove that existing operational data files are a viable data source and help broaden the data base for future studies.

II. DATA

A. SOURCES AND INITIAL PROCESSING

CDR W. G. Schramm extracted from the Fleet Numerical Weather Central (FNWC) BT history file all records whose locations, both temporal and spatial, were subject to the influence of any typhoon in the western Pacific during theperiod 1968 to 1972. The number of storms and individual storm tracks were recorded in the Annual Typhoon Reports of the Joint Typhoon Warning Center, Guam. All records in the BT history file were digitized from the actual traces, thereby reducing the chance of error incurred in radio transmission. Concomitantly, CDR Schramm extracted from the climatology files the long-term mean (LTM) thermal structure at the BT locations. The LTM is an all-years-monthly mean computed for each point on the FNWC's 63 by 63 point hemispheric grid. LTM values for BT locations that fell between grid points were obtained by the FNWC's Fields by Information Blending process. For each storm during the five-year period, BT records and LTM thermal structures were collated and filed along with the individual storm's characteristics. For each of the BT records, now grouped by storms, CDR Schramm calculated the quantities that express the individual BT's relationship to the storm as depicted in Figure 1. The two most important factors are the storm's CPA and the time before or after the CPA that the BT was taken. The computer printouts of the values of the LTM, the individual BT, and the calculated relationships were kindly provided to the author for analysis.

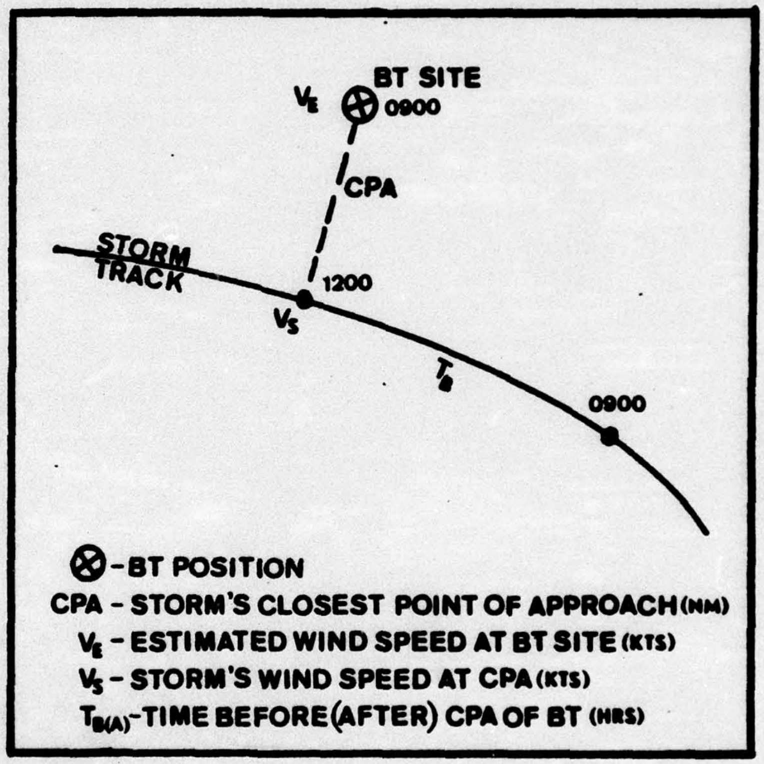

Figure 1. Calculated relationships between bathythermograph location and storm.

B. SELECTION OF STORMS

All 23 "super-typhoons" that occurred in the western Pacific during the study period were selected for the initial screening (Figure 2). Screening limits of $\pm$ 300 hours from the time of CPA, and CPA's less than or equal to 300 nmi, were used to ensure that only storm-influenced data entered the analyses. The interval of $\pm$ 300 hours reflects a total time period of 25 days centered on the storm passage, and the half-period (12.5 days) was large enough to provide sufficient data for the analyses. Since the purpose of this study was to examine the relationship between mixed-layer cooling and the distance from the path, a weighting scheme was devised which lent more credibility to the more recent temporal data. Data that were taken less than 24 hours from the time of CPA were given a weighting factor of 13, with a subsequent decrease of one weight unit per additional 24 hour period. Storm effects on the mixed layer are minimized at a distance of about 300 nmi from the storm path [Elsberry et al 1976]. Therefore, data were rejected that had CPA's greater than 300 nmi.

To offset seasonal variations in the MLT during the initial storm screening, the values of the MLT were normalized by subtracting the LTM values. By subtracting the before or after value of the BT MLT from the LTM value, a positive difference will reflect MLT cooling (Figure 3a-b). Then, for each storm, a curve was fitted to the before points and the after points by the least squares polynomial fitting method (Figure 3a-b). The linear curve for the BT's taken before the storm was to reflect the assumed uniformity across the storm track in the initial state. For BT's taken after the storm's CPA, a parabolic curve, suggested by modelling results [Elsberry et al 1976] and other data studies,

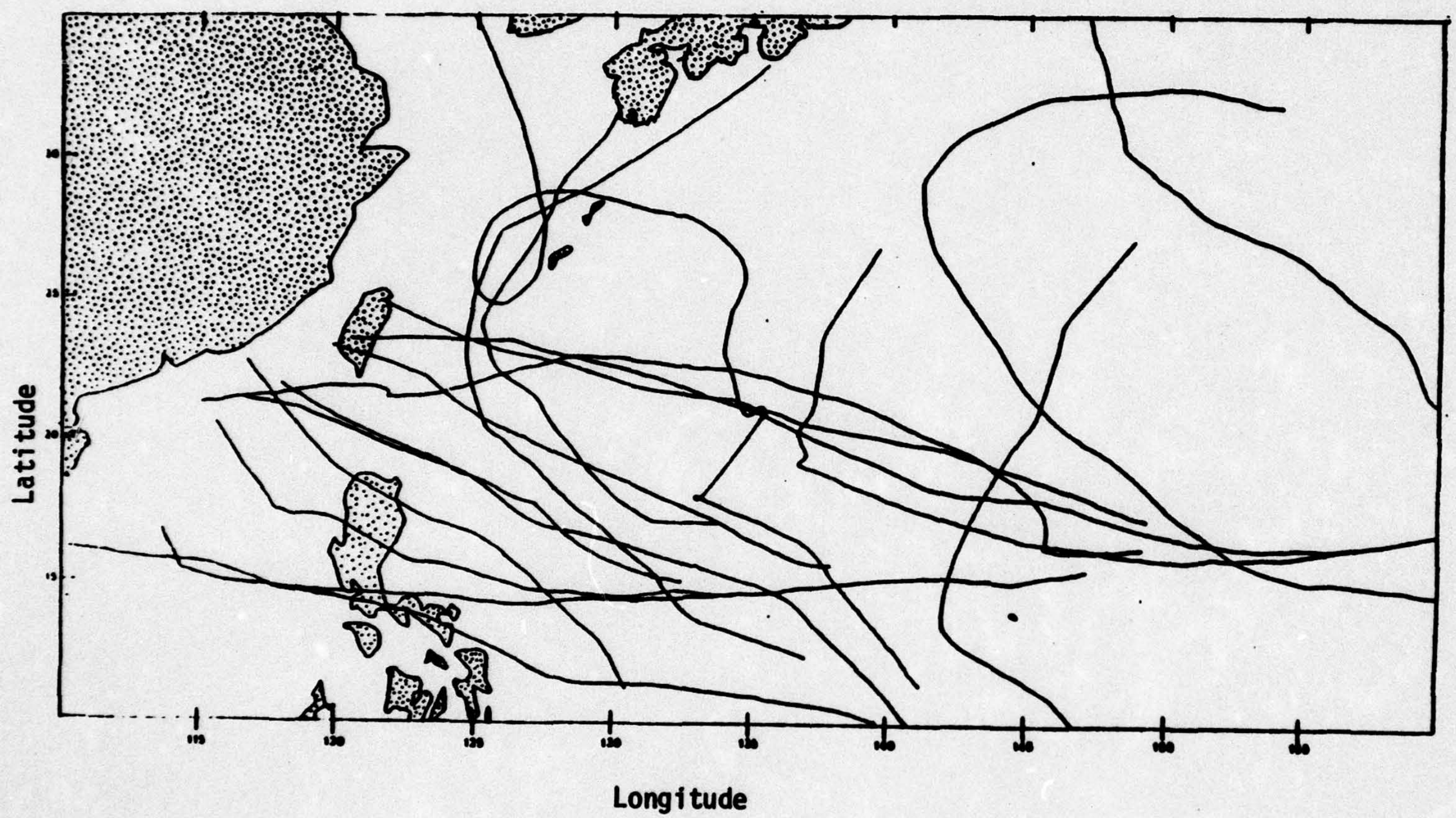

Figure 2. Composite of storm tracks.

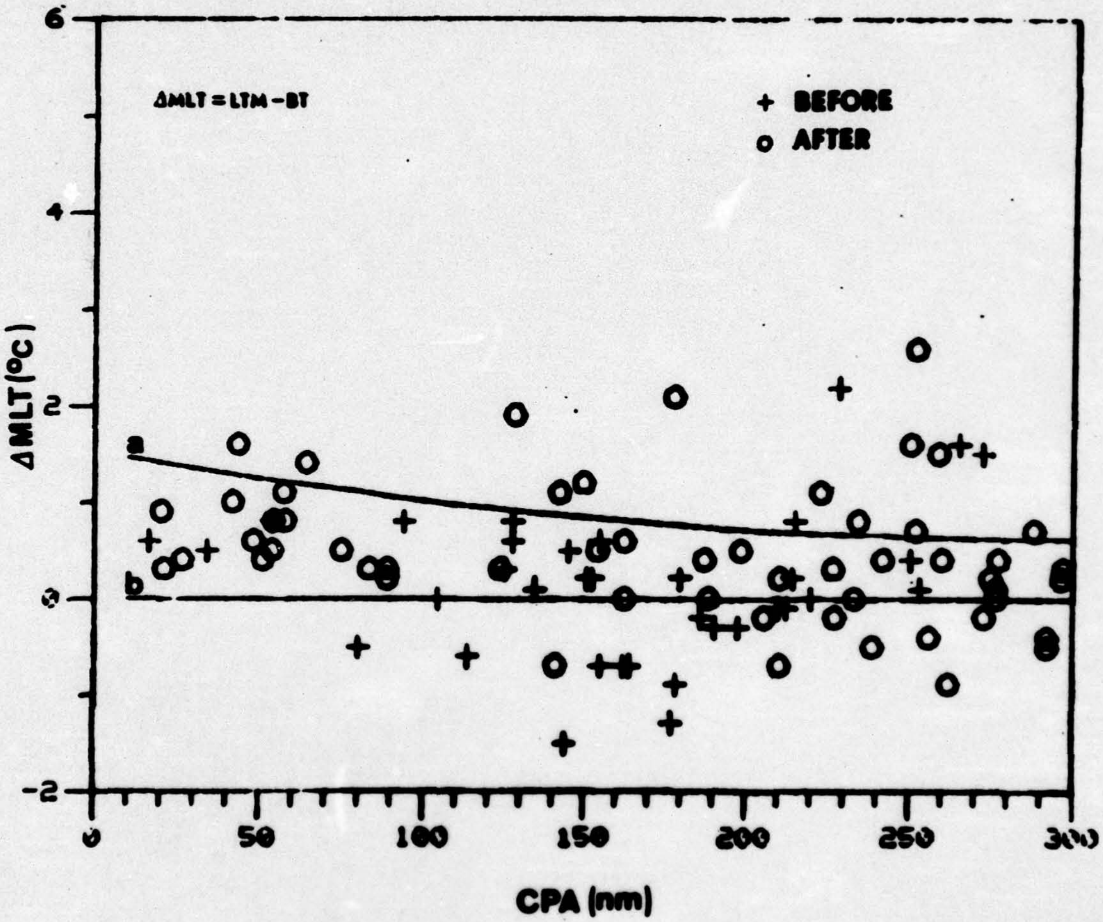

Figure 3a. Initial screening analysis of Typhoon Elaine 68/22. A linear curve (b) is fit to the before points. A parabolic curve (a) is fit to the after points.

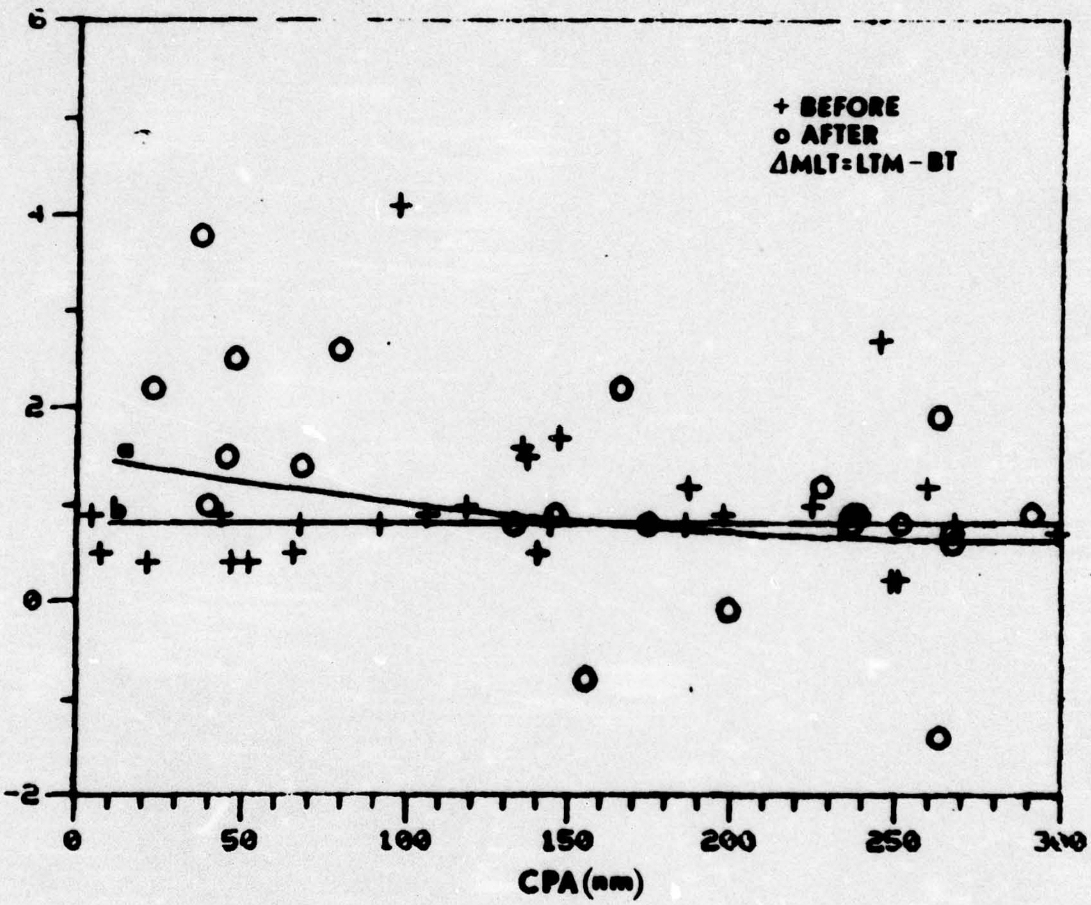

Figure 3b. Initial screening analysis of Typhoon Della 68/20. A linear curve (b) is fit to the before points. A parabolic curve (a) is fit to the after points.

was used to describe the cooling that has taken place in the mixed layer as a result of storm passage. In Figure 3a-b, the before curves, labeled (b), represent a uniform MLT approximately the same as the LTM and a MLT almost 1.°C cooler than the LTM, respectively. The after curves, labeled (a), demonstrate the degree of fit to the data achieved by using the parabolic curve. An important characteristic of the after curve in Figure 3b is the decrease to the state of the undisturbed mixed layer at the outer fringes of the storm's influence.

Of the 23 storms initially screened by this process, five were eliminated from further analyses because the quantity of data was insufficient to portray a realistic state of the mixed layer, either before or after the storm passage. Figure 4 represents a storm that was eliminated because the initial state of the MLT could not be realistically portrayed by only four before BT's. One additional storm was eliminated when investigation of the data taken before the storm passage revealed that much of the before data (31 BT's) were taken by the same vessel on two different course legs, and the MLT's were consistently 2.0°C cooler than the LTM (Figure 5). No other storm in the initial group displayed this condition of the MLT prior to storm passage. Because the data taken after the storm passage were from various vessels, it was decided to eliminate the storm to keep from introducing probable errors into the analyses. The results of the initial screening left 17 "super-typhoons" for additional analysis, with at least one storm in each year of the five-year study period.

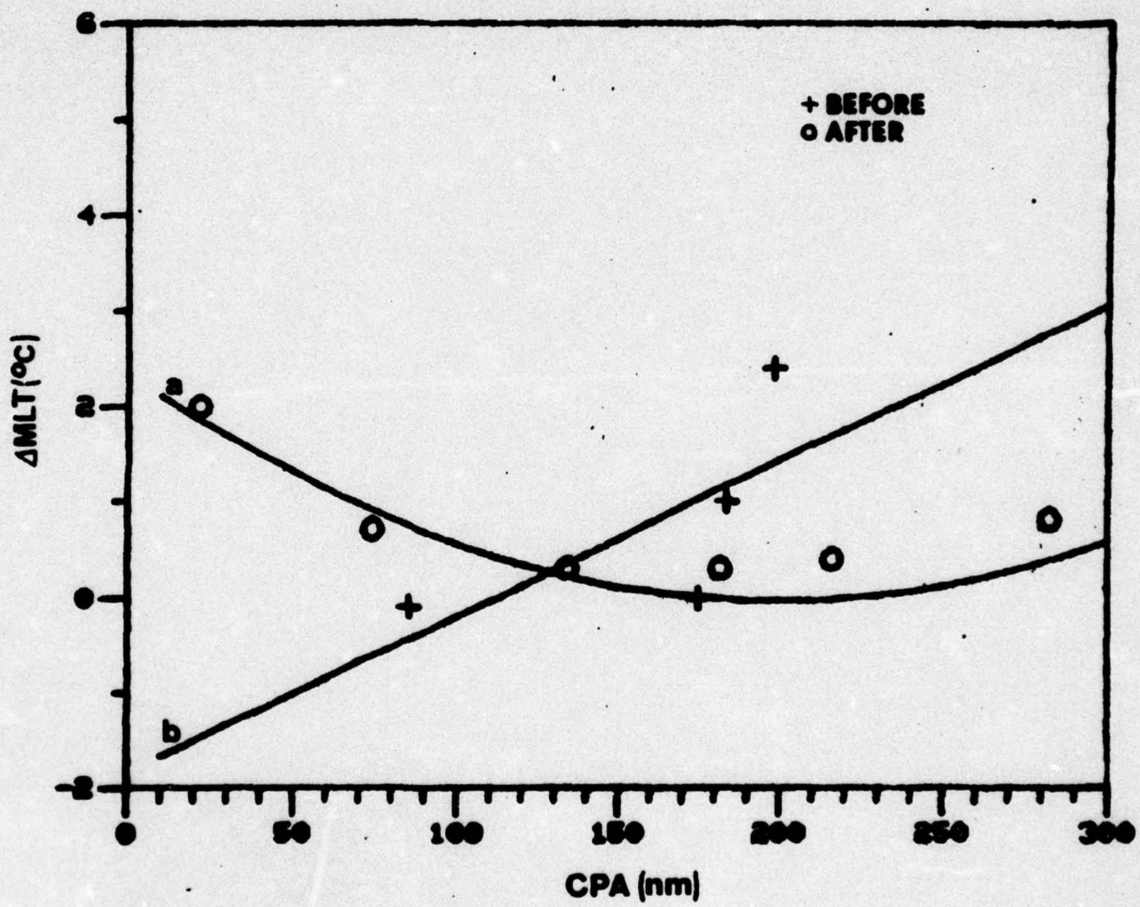

Figure 4. Example of typhoon (Anita 70/11) rejected due to insufficient data.

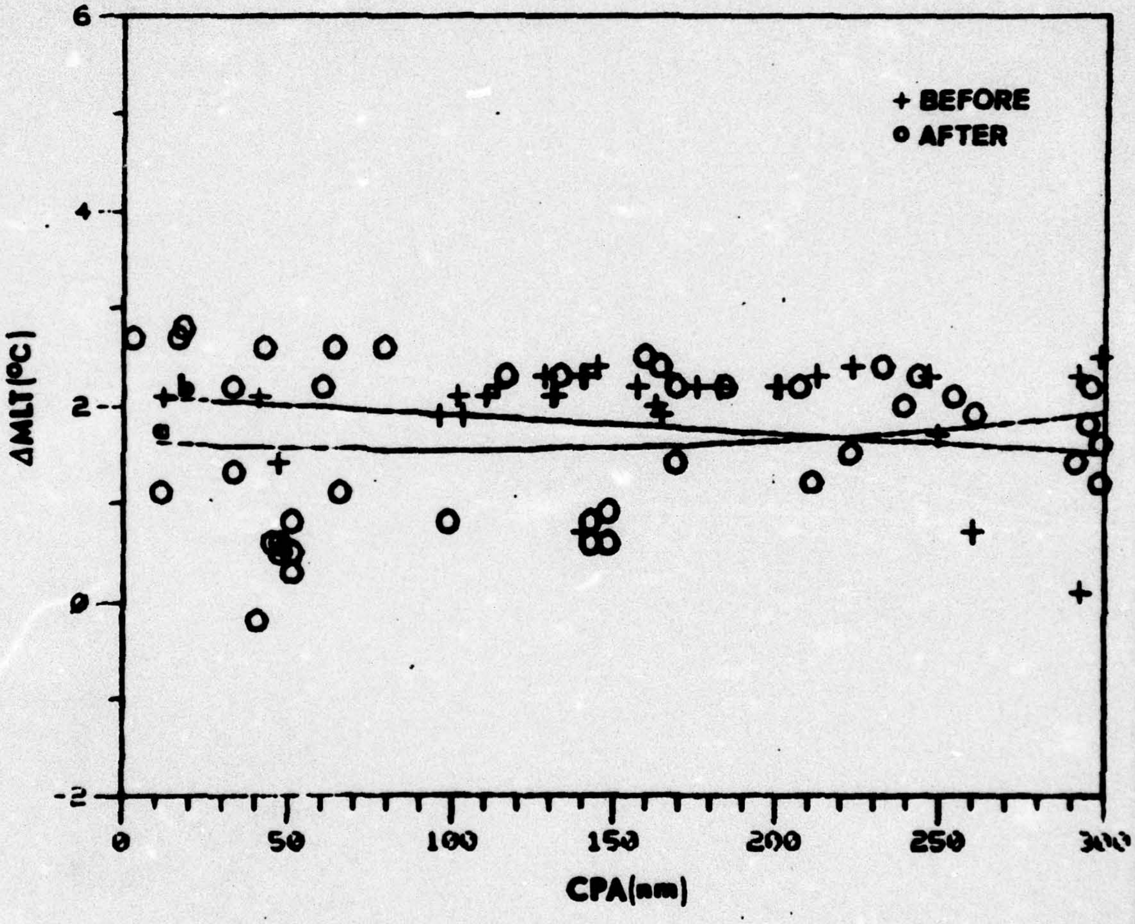

Figure 5. Example of typhoon (Judy 68/27) rejected due to temperature errors.

III. ANALYSES

A. ANALYSES OF STORMS

In the first composite analysis (Method 1) of all 17 storms, each individual storm was reduced to a data file that consisted of the difference between the before and after weighted curves (e.g. Figure 3a-b) in ten nmi increments. The differences for all storms were combined and a linear curve was fitted, again by the least squares method, to the resulting 570 points. In Figure 6, the line that represents the mixed-layer cooling has a slope of -.004°C/nmi with a maximum cooling, nearest the storm path, of 1.1°C. The arrows represent the standard deviations, ranging from values of 1.11 to .59°C. The extreme data range is represented by the dashed lines.

As a comparison and because each of the individual curves was subject to error, a second analysis technique (Method 2) was devised. The MLT's after the storm passage were normalized relative to the values of the linear before curves for all 17 storms. This created a data file of 397 BT records that represented the cooling in the mixed layer due to the storm passage. The results of this all-storms composite method of processing are seen in Figure 7. A weighted mean (circles), standard deviation (arrows), and extreme data range (dashed lines) were obtained for each 50 nmi range increment. An increment of 50 nmi was used to ensure a sufficient quantity of data, and it can be seen that the largest sample of 80 points, represented by vertical bars, fell within the 0-50 nmi increment. The mean mixed-layer cooling in

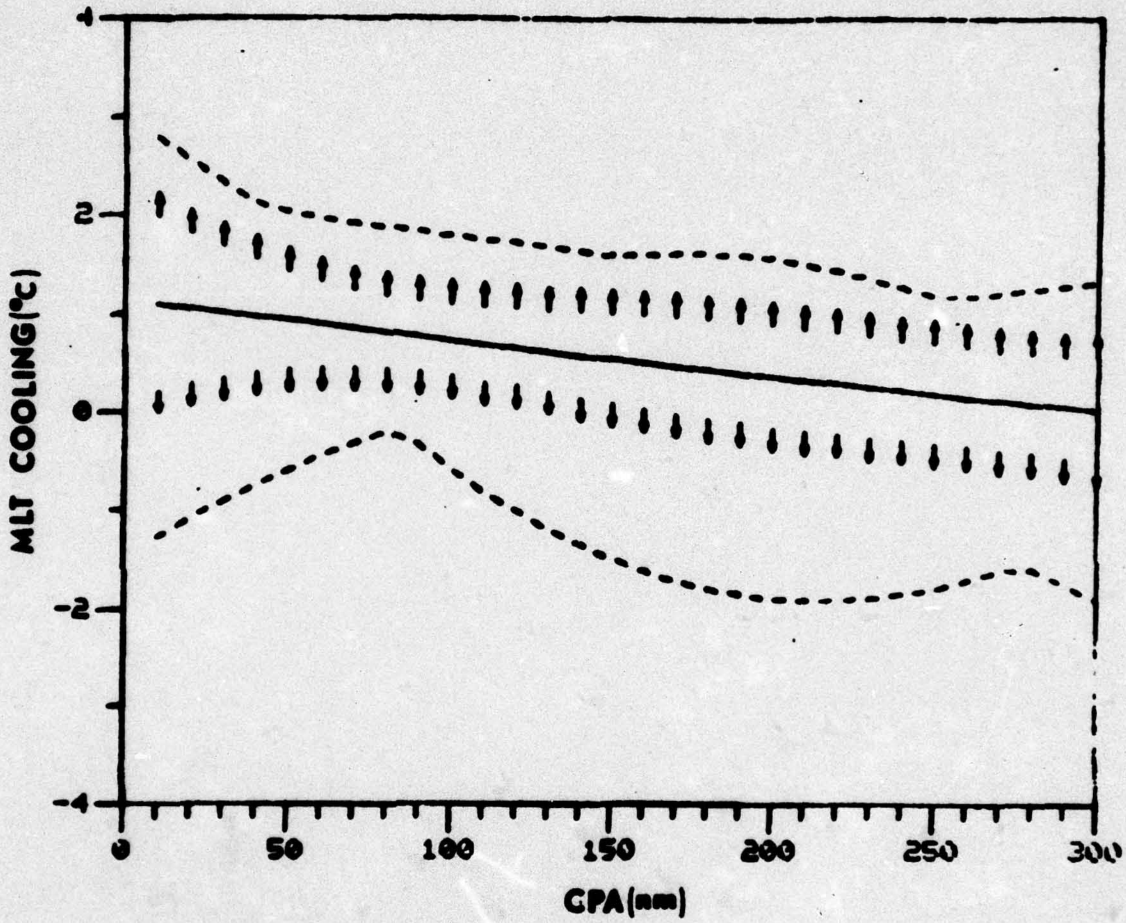

Figure 6. Mixed-layer cooling results from composite of curves for 17 storms. Arrows represent standard deviations in 10 nmi increments. Dashed lines are extreme data envelope.

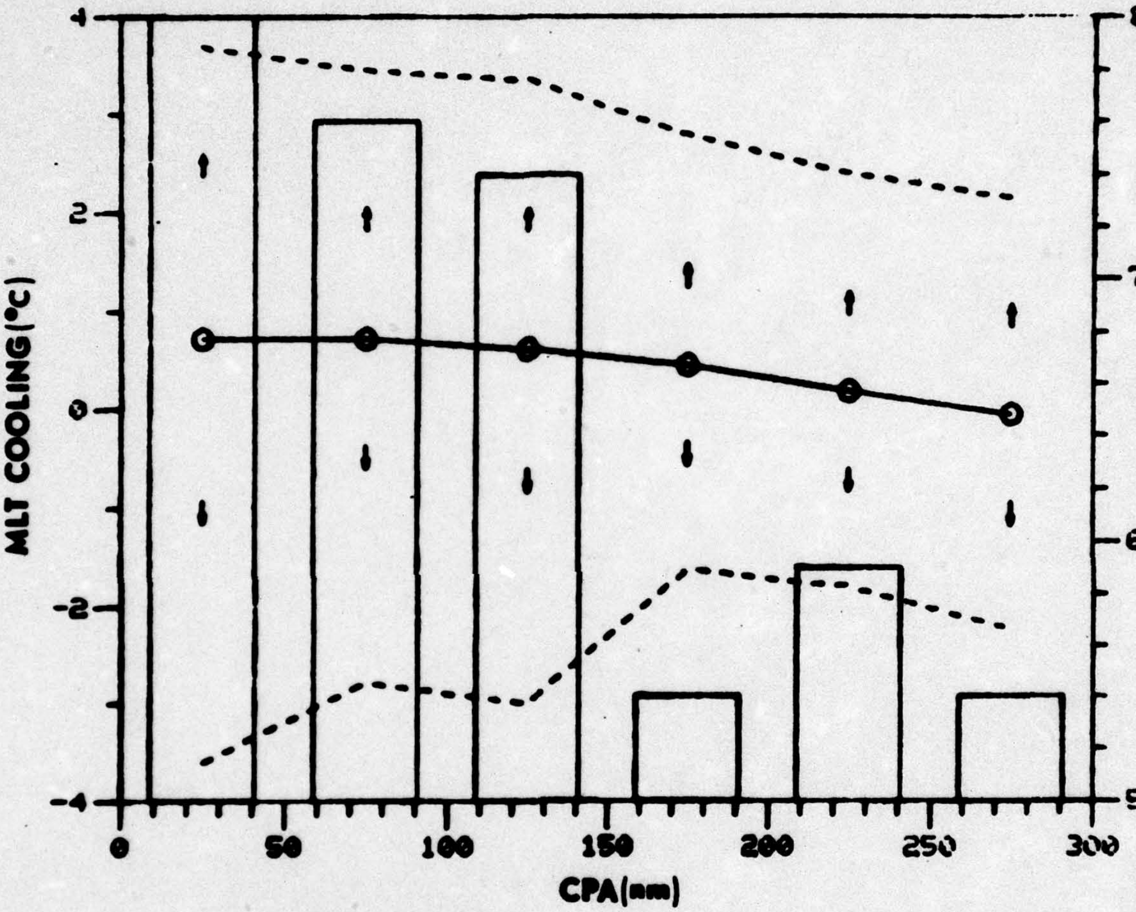

Figure 7. Mixed-layer cooling results from composite of actual data for 17 storms. Circles represent weighted means over 50 nmi increments. Arrows are increment standard deviations, dashed lines are the extreme data envelope, and vertical bars represent the number of BT's in the sampling increment.

the first CPA range increment was .72°C with a standard deviation of 1.88°C. Comparing the results of Method 2 with those of the fitted curves of Method 1 showed the hoped-for increase in MLT cooling was not present and that data scatter was extensive. Analysis Method 2 was modified in an attempt to decrease the amount of scatter about the means depicted in Figure 7. Only after BT's taken at CPA's when the storm was at or near the super-typhoon stage were to be analyzed. Consequently, all BT's in the after-storm file were eliminated if the respective value of the typhoon wind speed at CPA was less than 100 knots. As in Method 2, the means, standard deviations, and the data envelope in Figure 8 were calculated for the resulting 133 BT records. The extreme data envelope's size was decreased and the maximum mean cooling increased to 1.29°C. The anomalous increase in mixed-layer cooling between the first and second 50 nmi increment will be discussed in a later section. Figure 8 shows that the number of BT's in each sampling increment was generally uniform across the range, and, even though the scatter about the mean was somewhat reduced, it still did not reflect the expected magnitude of MLT cooling. A new approach to the analysis would have to be taken.

B. ANALYSES OF COUPLETS

After reviewing the data for the initial 17 storms, analysis Method 3 was devised to obtain a more precise representation of the mixed-layer changes. By plotting each BT's geographic position relative to the storm track, 138 "couplets" were found outside the influence of shallow water. Additionally, the couplets were subjected to the initial screening limitations of $\pm$ 300 hours from CPA and a CPA range of less

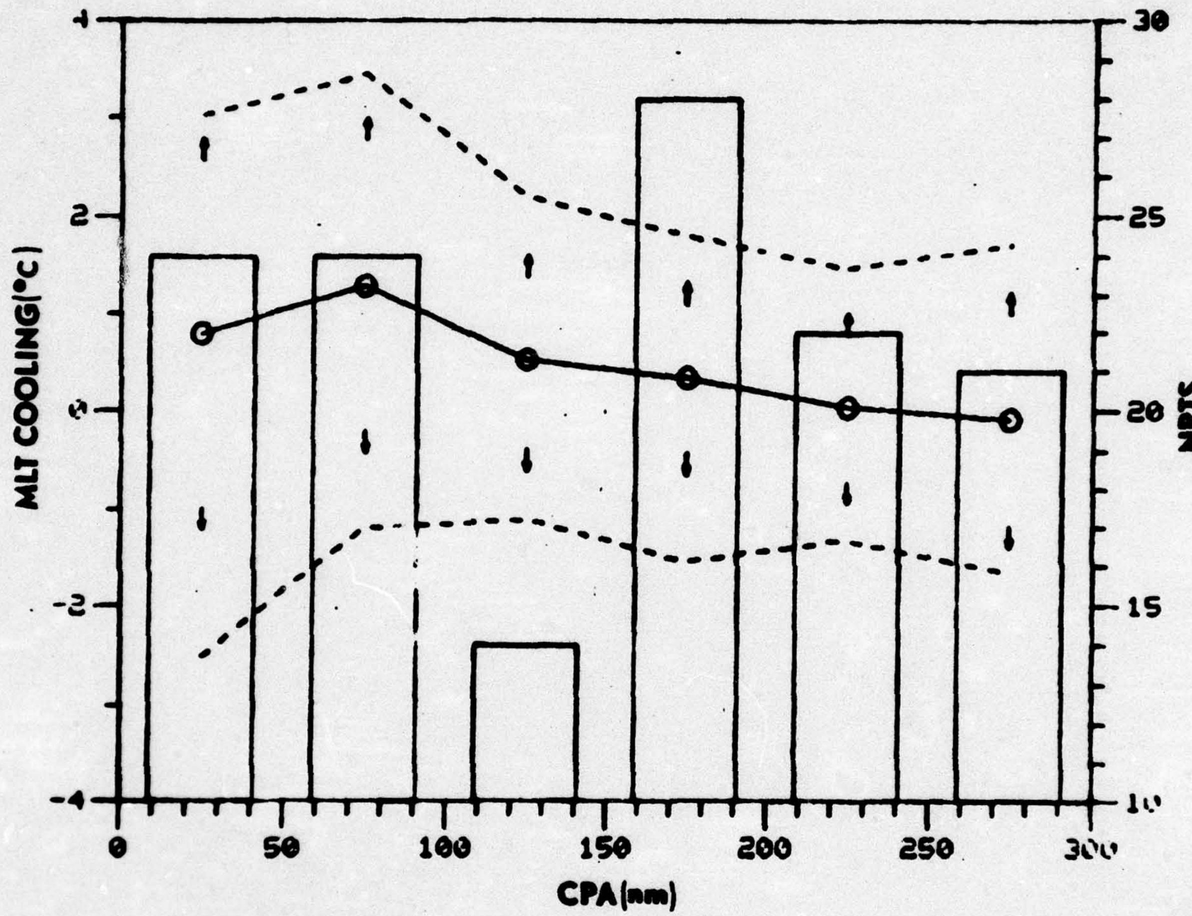

Figure 8. Mixed-layer cooling as in Figure 7 except for composite of actual data with typhoon wind speeds greater than 100 kts.

than 300 nmi. The couplet data file was a composite of data from 14 storms with each of the five study years represented.

To determine the magnitude of mixed-layer cooling that occurred at the couplet location, the MLT difference between the before BT and the after BT for each couplet was calculated and assigned a weighting factor as previously described. The weighting factor and the location (CPA) were determined by the position, temporal and spatial, of the after CPA BT. All couplet differences and a least squares linear fit to the data are depicted in Figure 9. The weighted line shows a maximum dcrease in the MLT of 1.75°C and a slope of .005°C/nmi. Analysis Method 3 yielded results that were more consistent with those of previous studies. As compared to Method 2 (modified) results, the maximum MLT cooling increased .46°C to a value of 1.75°C while the corresponding range of standard deviations was .1°C to 2.1°C (Figure 10). In reviewing the data file of the couplets it became apparent that, due to variations in storm intensity, some of the BT positions were not subjected to the influence of typhoon-force winds.

Analysis Method 3 (modified) examined all couplets and rejected 81 that had a typhoon wind speed at CPA of less than 100 knots. The majority of the rejected couplets were taken during the early growth and late dissipation stages of the typhoon at the larger CPA ranges. Cooling of the mixed layer due to storm passage in this method was 2.0°C (Figure 11) near the storm path. Method 3 (modified) also demonstrated that the storms showed little influence in altering the pre-existing MLT at the 300 nmi range. Although the maximum standard deviation increased from 2.1°C in the preceding analysis to 2.4°C, the correlation coefficient between the dependent (MLT cooling) and independent (CPA)

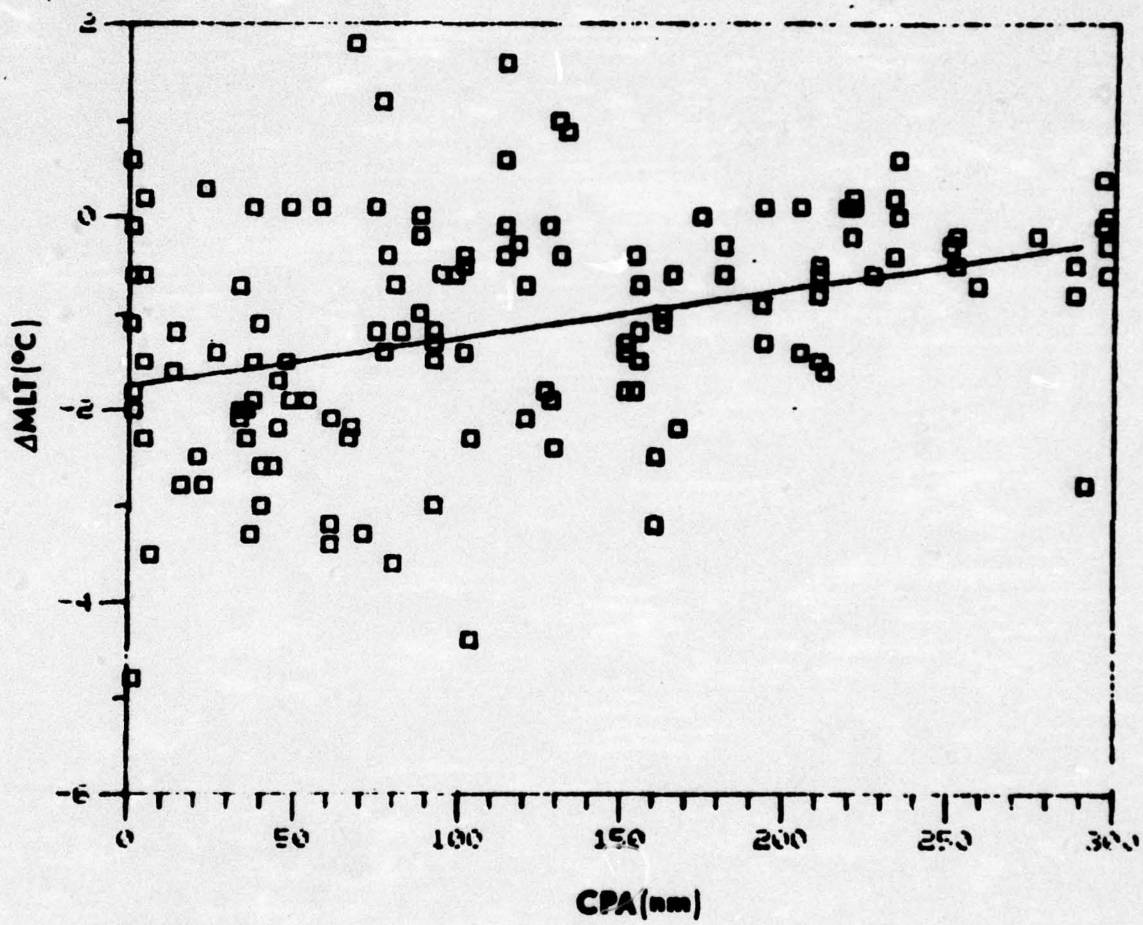

Figure 9. Decrease in mixed-layer temperature after storm passage. Squares are difference (°C) between the before and after couplet BT's.

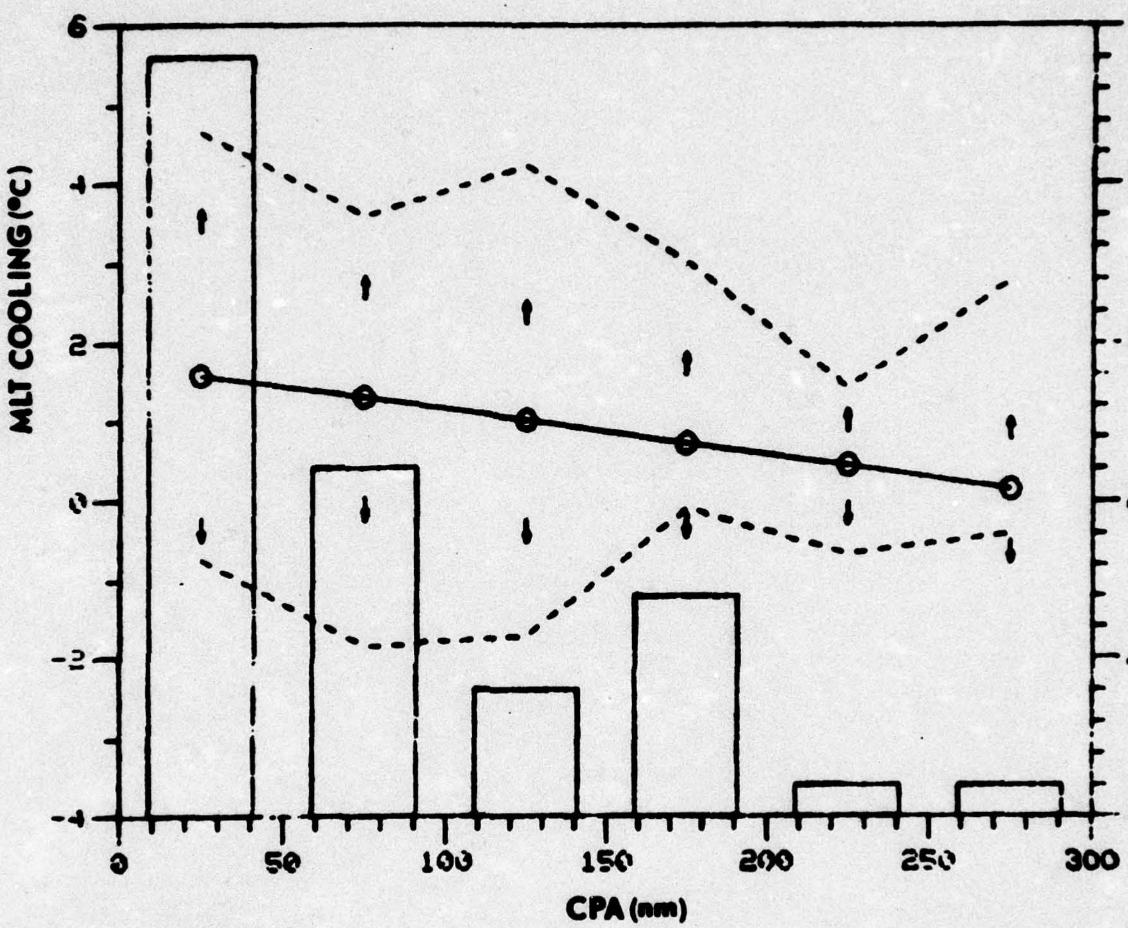

Figure 10. Mixed-layer cooling as in Figure 7 except for couplet analysis.

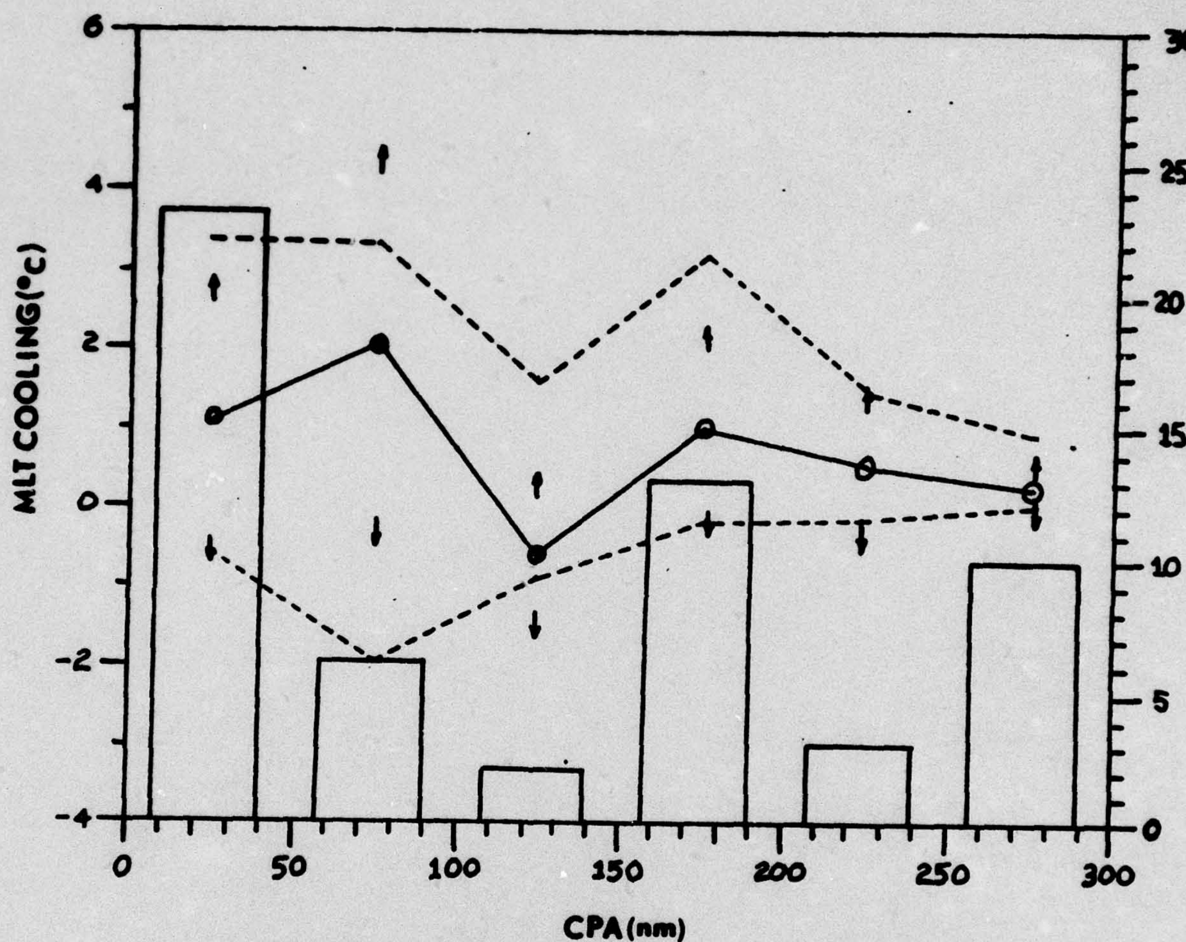

Figure 11. Mixed-layer cooling as in Figure 10 with typhoon wind speeds greater than 100 kts.

variables increased from .06 in Method 3 to .44. The 2.0°C cooling of the mixed layer near the storm path was reassuring because, even though the data file had decreased to 57 couplets, it represented a mean value for 14 storms.

Improvement over previous results obtained by Method 2 (modified) and Method 3 (modified) suggested further investigation of the relationship between the estimated maximum wind speed at the BT position and the mixed-layer cooling. The relation, $V_\theta r^{1/2}$ = constant [Riehl 1963], was used to estimate the maximum wind speed at the BT position, except that for BT positions inside the RMW the linear relation, V_θ / r = constant [Riehl 1963], was used. To establish the value of the constant for each storm the values of the RMW and the maximum wind speed were extracted, or interpolated, from the Annual Typhoon Reports. The 138 couplets used in Method 4 showed an extrapolated maximum cooling of 2.5°C and the standard deviations ranged from 2.58 to .86°C (Figure 12).

With the results of Method 3 and Method 3 (modified) in mind, an attempt was made to establish a correlation between the expected increase in the MLD and the decrease of the CPA of the storm. The 138 couplets previously selected and screened for Method 3 are displayed in Figure 13, with the linear least squares fit showing an increase in MLD ranging from .8 to 3.8 m. It can be seen in Figure 13 that the preponderance of near-zero MLD changes heavily influenced the fitted line. To eliminate the near-zero changes that were due to BT's being taken during the growth or dissipation stages of the storm, only BT's with typhoon CPA wind speeds greater than 100 kts were evaluated in the analysis depicted in Figure 14. The mean increase in the MLD after storm passage was 2.3 m and the standard deviations ranged from 2.66 to 8.18 m. The

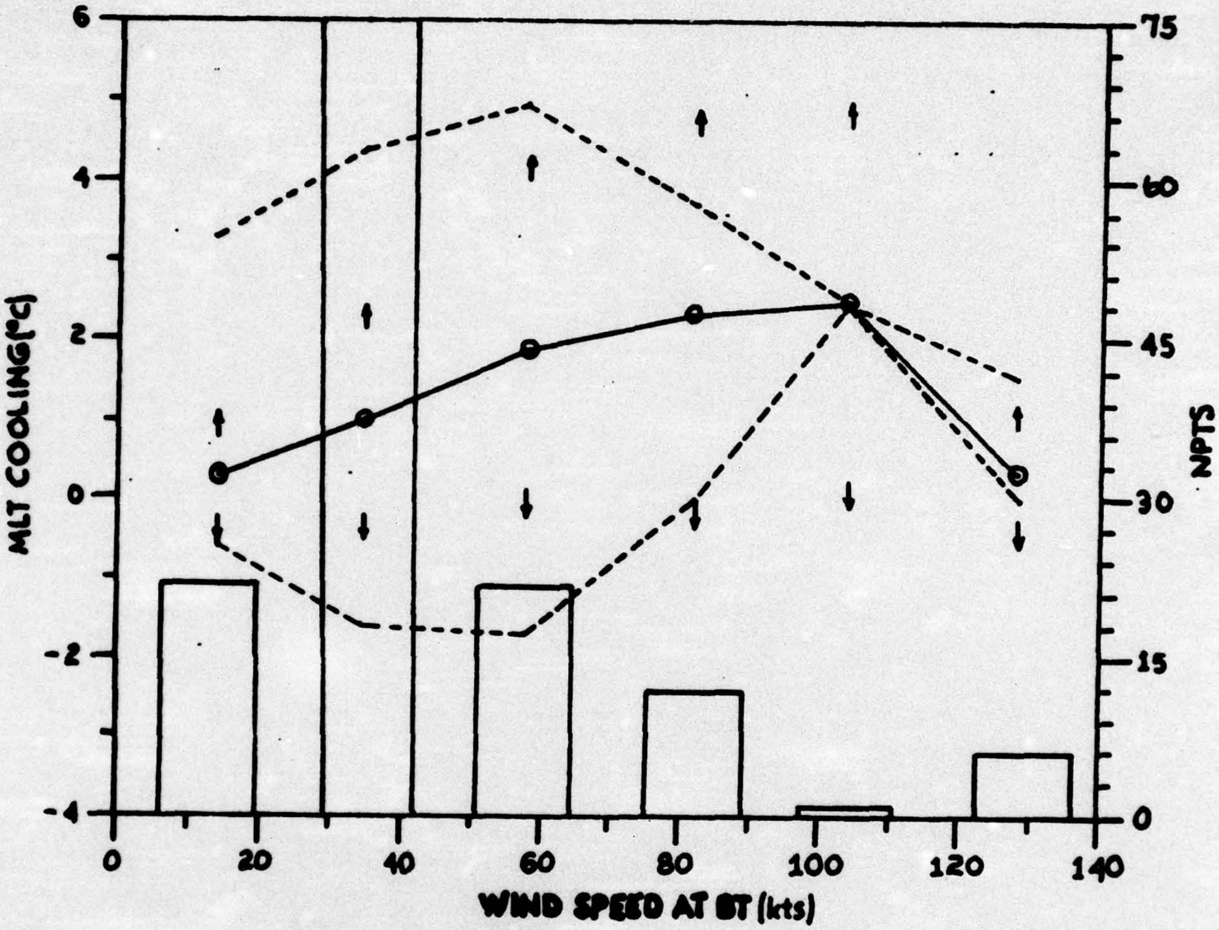

Figure 12. Mixed-layer cooling in relation to estimated maximum wind speed at BT position. Symbols as defined in Figure 11.

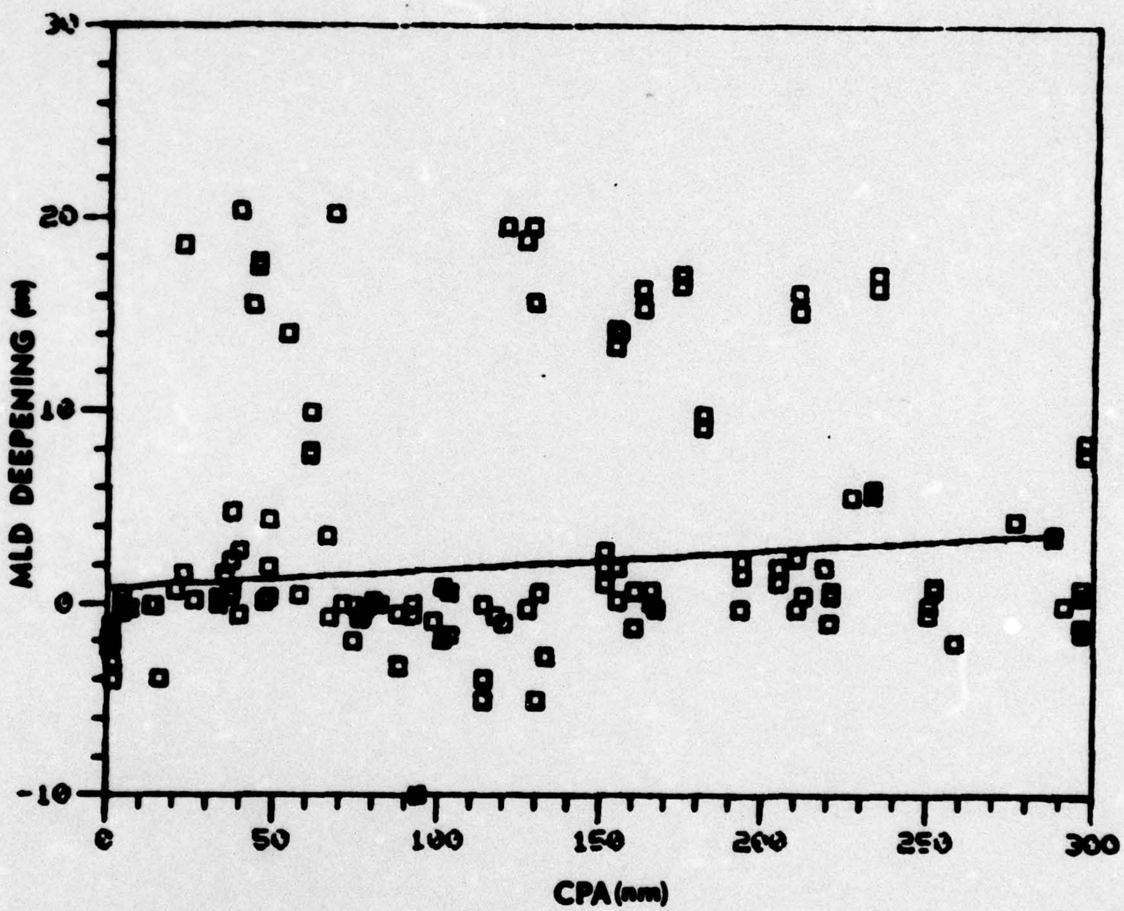

Figure 13. Change in mixed-layer depth with linear fit for all couplets. Squares are mixed-layer depth deepening after storm passage.

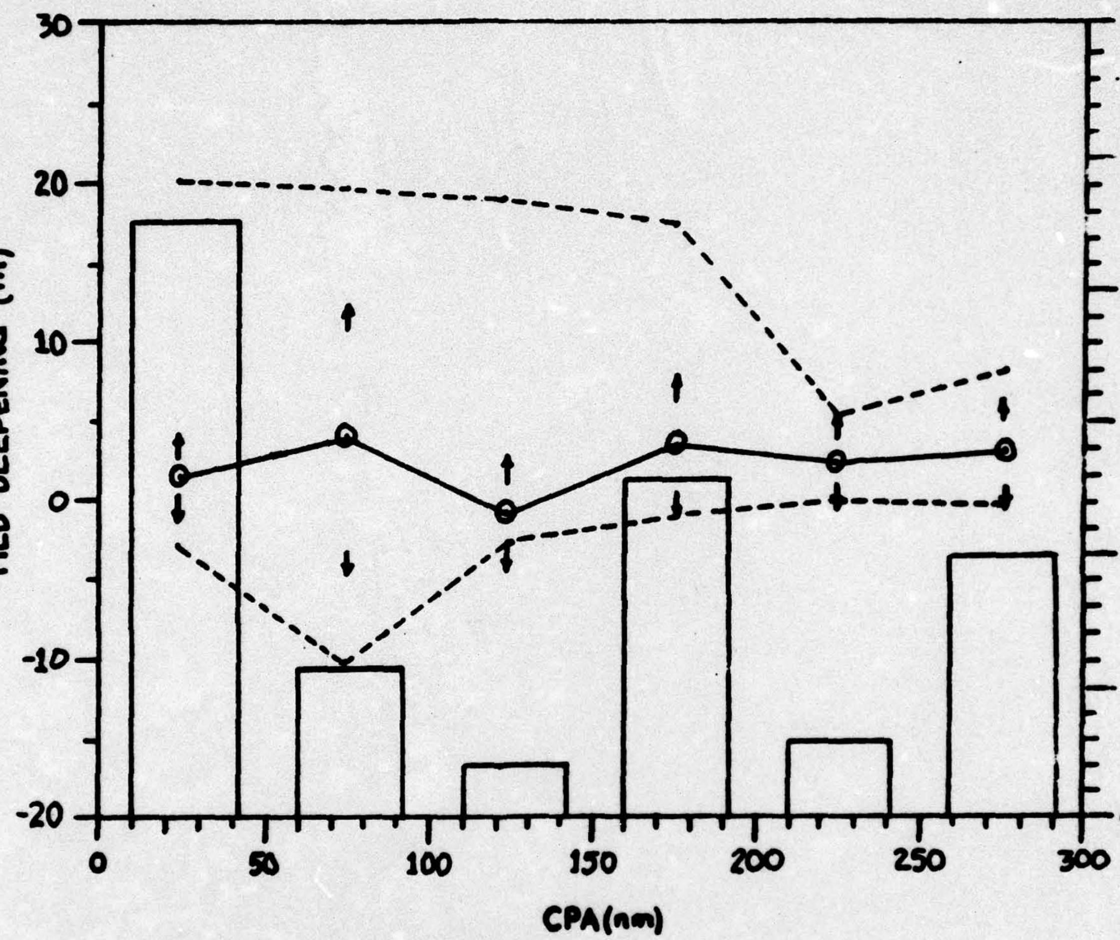

Figure 14. Mixed-layer deepening for couplets with typhoon wind speeds greater than 100 kts. Symbols as defined in Figure 11.

osition of the means within the data envelope again demonstrates the prevalence of near-zero data. 4.26 m was the largest mean change in the MLD depicted in Figure 14.

IV. DISCUSSION OF RESULTS

A. MIXED LAYER TEMPERATURE ANALYSIS

All analysis results are summarized in Table I. The initial composite curve results of Method 1 were promising, but it was suspected that estimation errors had accrued in the fitting of the after curves for some storms, due to the low density of BT's in the 0-50 nmi range. In the suspect storms the prevalence of BT's in the 100-200 nmi range had caused the curvature of the fitted parabola to be opposite of that expected for a physically realistic representation of the mixed layer after the storm. As with other analysis methods, the statistical significance of the results was established by use of the confidence interval test. Using the largest standard deviation, appearing in the respective analysis method, it can be stated with 80 percent significance that the mean cooling at or near the storm path was greater than zero for the results of Method 1. No problems were encountered with the use of near-zero slope lines (means) to approximate the state of the mixed layer before storm passage, and it was decided to carry this "uniform-ocean hypothesis" into the next analysis.

To overcome the estimation errors in the after storm passage portion of the previous method, Method 2 used the actual MLT differences from the after BT's coupled with the uniform-ocean hypothesis. However, this method introduced more scatter in the data that dropped the level of significance to 60 percent. The maximum/minimum cooling range of Method 2, as opposed to Method 1, (Table I) had increased in size and had probably influenced the mean cooling results near the storm path.

The increase in standard deviations also was consistent with the expanding extreme data envelope.

Method 2 (modified) was an attempt to increase the mean cooling by eliminating BT's from the portions of the storm path where storm intensity was not at or near the super-typhoon stage. By increasing the "signal-to-noise" ratio through the exclusion of weaker storms, a relatively large increase in mean cooling resulted. The anomalous increase in mean cooling between the first two sampling increments of Figure 8 was probably due to the decrease in statistical resolution incurred by the 66 percent reduction in BT files from the previous method. A line fitted to the means in Figure 8 would vary from the displayed means by less than two-tenths of a degree. Other statistical parameters in the results of Method 2 (modified) support the conclusion that MLT cooling at the storm path was approximately 1.3°C. The extreme data envelope decreased in size and the level of significance of the results increased to 75 percent, in spite of the fact that the standard deviation range increased. Evidently the uniform-ocean hypothesis provides a damping effect in the analysis by filtering out smaller scale variations in the MLT before storm passage. This effect, coupled with possible errors in the interpolated long-term mean values, implied that the couplet or "local-ocean thypothesis" should be the next analysis method.

The local-ocean hypothesis used in Method 3 was effective in that the test of the mean cooling being greater than zero was increased to a 90 percent level of significance. In addition to eliminating the LTM and estimation of errors from the analysis, it also ensured that a before BT, taken 150 nmi to the right of the storm track, would not be used

to represent the state of the mixed layer prior to storm passage for an after BT, taken 150 nmi to the left of the storm track. It was not expected that possible differences between the right and left side of the storm could be resolved with the existing operational data used in the present study.

Method 3 (modified) was a combination of the local-ocean hypothesis and the selection of more intense storms to insure strong surface forcing. Using only BT's taken when typhoon wind speeds were greater than 100 kts, as in Method 2 (modified), a mean cooling of 2.0°C near the storm path was obtained. Even though the cooling range, -1.8 to 3.4°C, represented a decrease from the previous method, the increase in standard deviations and the drop in the level of significance, to 85 percent, were probably due to the reduction of data to only 57 couplets. However, the results of Method 3 (modified) not only compared favorably with both modelling and previous studies, but they also indicated that a storm's influence on the MLT has terminated within a range of 300 nmi.

Any further division of forcing parameters would have reduced the quantity of couplet BT records to a size that would not be a representative sample. As a corollary, an analysis of the relationship between estimated maximum wind speeds at the BT location and MLT cooling was provided by Method 4. The results (Figure 12) indicate, as expected, the correlation between increasing estimated wind speed and increasing cooling of the mixed layer. The low density of couplets with estimated wind speeds in excess of 100 kts made it difficult to determine the magnitude of mixed layer cooling for BT positions subjected to super-typhoon force winds. The fact that Method 4 had the largest standard deviation of any of the previous analysis was due, in part, to the sparseness of data at the higher estimated wind speeds.

TABLE I

Summary of Results for Mixed Layer Temperature Analyses

ANALYSIS	NPTS	MEAN COOLING 0 CPA	MEAN COOLING 300 CPA	COOLING MAXIMUM	COOLING MINIMUM	RANGE OF STANDARD DEVIATIONS	CONF. INTERVAL
Method 1	570	1.10	.02	2.8	-1.9	1.11/0.59	80
Method 2	397	.72	-.05	3.7	-3.6	1.88/1.01	60
Method 2 (modified)	133	1.29	-.09	3.5	-2.5	2.00/0.97	75
Method 3	138	1.75	.25	4.8	-1.9	2.10/0.70	90
Method 3 (modified)	57	2.00	.36	3.4	-1.8	2.40/0.39	85
Method 4	138	2.50*	.33**	4.8	-1.9	2.58/0.86	80

*140 knots BT winds
** 0 knots BT winds

Method 1 - Fitted curves for 17 storms
Method 2 - Storm data for 17 storms
Method 2 (modified) - Storm data, Typhoon winds greater than 100 kts
Method 3 - Couplets for 14 storms
Method 3 (modified) - Couplets, Typhoon winds greater than 100 kts
Method 4 - Couplets, Relation to estimated BT wind speeds

Note: All cooling and deviations in °C
Confidence intervals in percent

B. MIXED LAYER DEPTH ANALYSIS

Method 5 was an analysis of the MLD changes with respect to the distance from the storm path for all couplets with typhoon wind speeds greater than 100 kts but, due to the oscillatory nature of the MLD after storm passage and possible poor timing of BT's the results (Table II) were inconclusive.

TABLE II

Results of Mixed Layer Depth Analysis

		MEAN DEEPENING		DEEPENING		RANGE OF STANDARD	CONF.
ANALYSIS	NPTS	0 CPA	300 CPA	MAXIMUM	MINIMUM	DEVIATIONS	INTERVAL
Method 5	57	3.0	2.8	20.4	-10.0	8.18/2.66	70

Method 5 - Couplets MLD analysis, Typhoon winds greater than 100 kts

Note: All MLD changes and deviations in meters
Confidence interval in percent

V. CONCLUSIONS

This study provided a "first look" at extensive files of existing operational data in an effort to formulate an empirical model of the oceanic response to typhoon passage. In addition, where most typhoon-related studies investigate storm effects in the narrow region of typhoon-force winds, this study has extended the sampling area to 300 nmi from the storm track. The BT files have proven to be a viable data source for evaluation of past storms and for storms where special data acquisition cruises are not possible. Overall, the results of this study were in agreement with previous studies in relation to the magnitude of cooling in the wake of a storm.

The couplet, or local-ocean hypothesis, method of analysis is, by far, the best of the two examined in this study. Future studies using larger samples of couplets from an expanded study period, should resolve the question of cooling differentials on opposite sides of the storm tracks. Additionally, the speed of advance of the storms in this study varied for each storm from stationary to approximately 20 kts. Since the net cooling is proportional to the time the location is acted on by the storm, and thus to the speed of advance, an analysis of this type is indicated. Another fact determined by this study was that typhoon influence had been minimized within 300 nmi of the storm path. Using an expanded, more than five years, study period and, possibly, typhoons of less than "super" intensity it would be most valuable to obtain insight into the actual distance at which the storm's influence is considered negligible.

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